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Abstract

The marine renewable energy industry is expanding globally in response to increased energy demands and the desire to curtail greenhouse gas emissions. Within the UK, Wales has the potential for the development of diverse marine renewable technologies, with a strong tidal range resource, areas of high tidal current energy, and a spatially limited wave energy resource. Targets have been set by the Welsh Government to increase the contribution of marine renewable energy to Wales' electricity generation, and the recent introduction of demonstration zones for tidal and wave energy aims to facilitate developers in device deployment. However, uncertainties remain about the potential impacts of devices, particularly for array scale deployments, planned at several sites, and for the extensive structures required to capture the tidal range resource. Here we review present knowledge of potential impacts, including physical, ecological and societal dimensions, and outline research priorities to provide a scientific basis on which to base decisions influencing the trajectory of Welsh marine renewable energy development.

Keywords: Wave energy, Tidal lagoons, Tidal energy, Socio-economic impact, Ecological impacts, Electromagnetic fields

1. Introduction

In response to international concern surrounding the impacts of climate change, the UK government has committed to ambitious carbon emission reduction targets of 34% by 2020, and at least 80% by 2050 [1]. To achieve these targets, it is estimated that 30% of UK electricity will need to be generated from renewable sources by 2020 [2]. Renewable energy from marine resources are expected to form a key portion of this future energy mix—an assessment of the UK's theoretical marine energy resource indicates a potential total annual energy yield of 285 TWh from wave, tidal range, and tidal stream resources [3], compared to a current annual electricity demand of approximately 303 TWh for 2014 [4]. However, this marine resource is subject to both technical and economic constraints, and so the practically exploitable resource will be considerably less.

In the UK, coastal waters around the country of Wales, bordered by the Irish Sea to the north and west and the Bristol Channel to the south, hold a significant portion of this UK marine energy resource; a governmental study assessing the entire UK theoretical resource suggests approximately one seventh of the wave energy resource, one quarter of the tidal range resource, and one third of the tidal stream resource [3,5]. Recognising the value of this marine renewable energy resource, the Welsh Government set ambitious targets, aiming to capture at least 10% of the potential tidal stream and wave energy by 2025 (equivalent to 8kWh/day/person of the mean consumption of 22kWh/day/person), and also committed to investigate where tidal range technologies may be appropriate around the coastline [6].

There are substantial challenges associated with the technological development and commercialisation of marine renewable energy that are required to achieve the Welsh Government's targets, such as: 1) accurately quantifying the 'real-life' performance of individual devices, 2) uncertainty in terms of the outcomes of consenting processes, political will and government subsidy, 3) potential ecological impacts and unanticipated environmental effects, 4) public acceptance and community engagement, and 5) cumulative effects when devices are installed at array scale. In order to facilitate the work required of developers to address some of these issues, the Crown Estate, as managers of the UK seabed, announced the lease of UK seabed rights for six new wave energy and tidal stream ‘demonstration zones’ to third party managers in July 2014. One wave demonstration site, and two tidal stream demonstration sites are located off the Welsh coastline, in the waters surrounding Pembrokeshire and West Anglesey respectively (Fig. 1).

Thorough scientific evidence to underpin policy decisions on MREIs (Marine Renewable Energy Installations) is incomplete—particularly for tidal lagoons where few comparable developments currently exist globally. The wave and tidal stream demonstration zones, together with proposed tidal lagoon developments, means that Wales has the full range of marine renewable energy technologies under active development, and contains the sites where several developers plan to scale up from single test devices, to multiple device demonstration sites and commercial arrays.

Thus, in addition to increasing our knowledge of ‘primary’ impacts, there is the potential for cumulative impacts and multiple device/array interactions, which are difficult to predict on the basis of existing data, and tend to be based exclusively on theoretical modelling studies [e.g. 7]. The impacts from proposed MREIs are wide-ranging, and encompass a mixture of positive and negative socio-economic impacts (e.g. combined recreational and aquaculture use, coastal defence, altered coastal aesthetics), as well as potentially deleterious environmental effects (e.g. sediment transport). These potential impacts require careful consideration, as Welsh coastal and inshore areas have a wide range of sites designated for species and habitat conservation goals, as well as heritage and aesthetic values, and consideration is being given to expanding existing Marine Protected Areas (MPAs; Fig. 2).

Here, following a brief description of current developments we outline current knowledge of the likely impacts of marine renewable energy developments, and from this highlight research gaps which should be addressed to reduce uncertainty and inform the decision making and consenting process within Wales.

2. Marine renewable energy developments

2.1. Tidal Stream

Several areas around the Welsh coastline have a sufficiently powerful tidal stream resource to be considered as sites for tidal stream devices. These are concentrated within narrow channels and around headlands, where the constriction of flow accelerates the tidal current (such as to the West and North of Anglesey and off the Pembrokeshire coastline) and can be seen in Figure 1. The Crown Estate has estimated that each of these areas has a potential installed capacity of 2–4 GW, but research suggests that with technological developments the tidal-stream energy resource could be much higher if deeper water and lower flow sites were developed [5]; such as the partial amphidromic point off Ireland (see Fig. 3).

The predictability of tidal stream energy is highly attractive to developers, and eases grid management issues compared to other stochastic renewable energy forms [8]. Potential TEC deployments around Wales include several forms of device, such as horizontal/vertical axis turbines, oscillating hydrofoils and tidal kites, as reviewed in [9]. Although studies to predict performance have been carried out for many of these devices, optimal siting, resilient design, and the interaction between the device, the resource, and the environment are topics of active research [7,8,10,11].

2.2 Tidal Range

Substantial potential exists for tidal barrages and tidal lagoons to contribute to renewable electricity generation within the UK. There is particular focus on Wales, because of the large tidal ranges in both South Wales [>12 m; 12], and in North Wales [>8 m; 13], and the potential to contribute to tidal phasing solutions for constant electricity production in conjunction with tidal-stream energy [5]. By far the largest potential contribution of marine renewable technologies to the UK's energy demand could be from tidal barrages—at least 10%, or ~22 GW could come from the Severn Estuary alone [12]. However, barrage design proposals for the Severn Estuary, developed since the 1970s [14–21], have failed to gain governmental support, due to significant environmental implications and high capital cost [22,23]. The Severn Tidal Power Feasibility Study concluded that the obstacles to a Severn Barrage scheme were too great for public investment [1,24]. Therefore, we will limit our scope to reviewing tidal lagoons, although the processes and impact of lagoons and barrages are often intertwined.

The indicative annual energy resource from tidal lagoon schemes has been estimated as 2–4 GW in the Severn Estuary area, and 4–8 GW along the North Wales coastline [3,7]. There is spatial variability in the phasing of tidal range around Wales; north and south coasts are approximately 4 hours out-of-phase with one another (Fig.

3), meaning that energy intermittency issues throughout the day could be minimised if lagoons were strategically constructed both in the north and south. However, variation in power generation also exists over the lunar cycle (spring and neap tides). A proposed tidal lagoon in Swansea Bay [25,26] has been granted development consent by the Secretary of State for Energy and Climate Change in June 2015. The lagoon development would be projected to have a rated capacity of 320 MW by 2018. Plans also exist for tidal lagoon developments at several additional locations around the Welsh Coastline (Fig. 1). A much larger proposed tidal lagoon between Cardiff and Newport would have an installed capacity of 1.8 to 2.8 GW, dependent on final design [27,28].

Several developers have interest in areas along the North Wales coast as sites for tidal lagoons, where spring and neap tidal ranges are approximately 7.5 m and 4 m, respectively [>12 m; 12,29]. Through an initial model study of large-scale lagoon designs in North Wales, Angeloudis et al. [29] predicted that power generation in this region is not plausible during neap tides, because of the small tidal range. Angeloudis et al. [12,29] also calculated that, for their lagoon designs, approximately 38% of the annual potential energy could be harnessed, acknowledging the effects of intertidal hydrodynamics and turbine/sluice gate specifications. Moreover, the harnessed energy could be reduced further if other lagoons were built in the vicinity.

2.3 Wave Energy

The theoretically extractable annual mean UK wave power resource has been estimated as 43 ± 4 GW [30], with long-term annual mean wave power levels along the western UK coastline ranging from 25–75 kW m^{-1} [31,32]. The highest concentrations of wave power around the Welsh coastline are in areas to the southwest, which are exposed to the Atlantic Ocean (Fig. 4). The UK Atlas of Marine Renewable Energy Resources, estimates the theoretical annual mean wave power density to be 15–20 kW m^{-1} close to the Pembrokeshire coastline, with areas further offshore approaching 30 kW m^{-1}; however the spatial and temporal resolution of the data used to produce these estimates is very coarse. Indeed, inter-annual and inter-decadal variability of the resource needs to be considered to enable optimal site selection and accurate device performance projections by developers [33].

Wave Energy Converter (WEC) devices are based on a wide range of operating principles, as reviewed in [34,35], with varying extraction efficiencies, and optimal location in terms of depth and wave climate. Devices may be broadly categorised according to distance from the shoreline; either onshore, nearshore or offshore [32], with associated differences in both engineering challenges and performance parameters. Accurate characterisation of WEC device behaviour is needed for accurate technical resource estimates [36,37], and essential in determining the potential for WEC devices to generate electricity in Welsh coastal areas.

There are three sites currently undergoing feasibility studies for the deployment of WEC technology in Wales, all off the south Pembrokeshire coast, and in close proximity to Milford Haven port. The Crown Estate wave demonstration zone managed by WaveHub is a 90 km^2 area sited ~20 km from shore in 60 m water depth. Wave Dragon Limited have proposed a smaller site in similar depths to the west of the demonstration zone, whilst Marine Energy Limited have proposed a nearshore site off St Govan's Head. No devices are presently deployed; however, Swansea-based Marine Power Systems have planned the testing of a scale version of their Wavesub device at the Haven Waterway Enterprise Zone in 2017, prior to a full-scale device being tested in the demonstration zone in 2019.

3. Physical impacts and research priorities

3.1 Tidal stream technology

Recent studies have indicated the likelihood of environmental impacts and changes to hydrological regimes associated with extracting energy from the tides [10,38,39]. The primary impacts of TECs are the impacts of the structure and the energy extraction on hydrodynamics and morphodynamics (sediment transport). The physical presence of a TEC and its foundations alters near-field hydrodynamics and sediment dynamics during both installation and operational phases. The turbine motion of tidal stream devices also impacts turbulence and dissipation in the area surrounding a device [40].

Power extraction by TECs reduces the kinetic energy of the tidal currents in comparison to the undisturbed resource. Extracting tidal stream energy can also influence water surface elevations, although this impact is thought to be minimal [7]. Through alteration of the tidal currents, tidal steam energy extraction has the potential to cause spatial and temporal variations in sedimentation and erosion rates [39]. The magnitude of this impact on sediment dynamics increases with the degree of tidal asymmetry at the point of extraction [39], therefore the magnitude and nature of tidal asymmetry should to be considered alongside the magnitude of the tidal currents when considering potential sites for situating TECs.

The potential for full-scale (300MW) arrays of TECs to change larger-scale far-field sediment dynamics, such as the maintenance of headland sand banks has been identified [7]. Sand banks play an important role in coastal defence through depth induced wave breaking, and can influence the condition of adjacent beaches through sediment exchange [7,41]. Recent modelling studies have begun to quantify the magnitude of impacts on the sedimentary processes affecting sand banks, and indicate that ‘first generation’ (<50 MW) TEC array sizes would result in sedimentary impacts within the bounds of natural variation at tidal sites off northwest Anglesey [42].

The near-field effects of TECs on flow can be modelled numerically or can be observed in physical laboratory experiments. However, there is considerable uncertainty regarding the magnitude of these effects, as the impacts of prototype devices (at pilot scales) may not translate to the impacts from commercial-scale arrays. Although some modelling studies exist [7,11,43], many impacts from scaling up test devices into commercial-scale arrays remain unknown, as the interactions between the impacting processes and the cumulative effects of tidal energy extraction are highly site-dependent. For example, for a single TEC operating in a steady flow, there is a deceleration of the tidal current speed immediately upstream as well as downstream of the device, with accelerated tidal current speed (and turbulence) around the device, and a turbulent wake downstream. Moreover, energy extraction in resource models tend to be implemented as depth-averaged processes, and as the interaction between devices and the resource are non-linear, three-dimensional, and with temporal variability to current speed and turbulence; hence much more research is required to resolve turbine behaviour in hydrodynamic models before impacts can be fully resolved.

3.2 Tidal lagoons

3.2.1 Inside lagoons:

A primary impact of the physical tidal lagoon structure is that natural tidal and coastal currents will decrease or be completely absent (during the water holding periods) within the lagoon [13,44]. Most importantly, reduced energy and tidal pumping inside the lagoon will alter sedimentation patterns and sedimentary features, with the most obvious effect being scour occurring near turbines and sluices, and siltation elsewhere [45]. Vertical mixing will be reduced (away from turbine wake), hence concentrations of suspended sediments and other materials will be reduced, and light penetration and stratification will be increased; all of which could result in water quality problems [43,45]. For example, there may be a build-up of physical and chemical contaminants due to reduced flushing, or re-suspension of contaminated sediments in regions of scour [45]. In addition, increased light may stimulate primary productivity increasing the risk of eutrophication and altering nutrient flow as phytoplankton deposition occurs [45].

By concentrating turbines in one section of the lagoon wall (sometimes called the power house), counter-rotating eddies may form in the turbine wake [14,44], which could impact the marine environment resulting in localised sediment resuspension, scour, and water quality impacts. Instead, Falconer et al. [14] recommended evenly spacing turbines throughout the whole lagoon structure. In practice, this may not be feasible due to bathymetric or other constraints.

Lagoons may cause a loss of intertidal areas within the structure, since the surface-level range will be reduced, compared with the natural tidal range. One potential benefit will be reduced coastal flood risk for lagoons which are connected to land—a circumstance that is particularly relevant to the North Wales coast [13]. During extreme storm events, for example, turbines could be shut off to prevent flood flow impacting the coastline within the lagoon wall. A detrimental environmental effect of a reduction of intertidal area is the loss of intertidal habitats for resident and migratory species; for example, loss of salt marshes, soft sediment biota, rocky shore species, and *Sabellaria* biogenic reefs. Lagoon or barrage structures in estuaries would, on the whole, negatively impact on habitat conservation, water quality, and ecosystem services [45]. Despite this, tidal ranges and potential energy yield are maximal in estuaries, thus ultimately benefitting the wider environment through reduced carbon emissions [45]. Therefore, tidal range development siting should carefully weigh up the resource and anticipated environmental interactions, particularly for estuarine locations.

3.2.2 Outside lagoons:

The alteration of the natural physical environment outside of lagoons will depend on the regional hydrodynamics and atmospheric conditions, local topography and bathymetry, the design of the lagoon, and the operational specifications of the lagoon [13]. Clearly, the larger the area of the lagoon, the greater the power output and the greater the alterations to the physical environment [44]. Processes that are likely to be impacted are scour near the lagoon, sediment supply to beaches and sand banks/bars, and wave reflection/diffraction. Sediment starvation to sand banks, sand bars, and beaches may impact the ability of these features to absorb the energy of winter storms, protecting the coast from wave erosion [7,42]. Sand banks/bars are also important nursery and breeding grounds for many fish species [45].

Away from the turbines (i.e., > 50 km), the hydrodynamic effects are likely to be minimal, although simulated tidal range increased in Boston, USA, by a few percent, as a result of possible lagoon designs located within the Bay of Fundy, Canada—simulation with sluice gates always closed (i.e., no power generation) produced maximum change in tidal range [44]. Therefore, as Wolf et al. [45] also alluded to, far field flood risk could be increased due to large-scale lagoon structures. Hydrodynamic impacts of lagoons in near resonant systems, such as the Severn Estuary, are likely to be pronounced [44]; affecting flood risk both in the near-field (due to altered sedimentation and beach morphology) and in the far-field (due to altered tidal regimes). Lagoons may also affect the strength of residual currents and positioning of frontal systems, where stratified and mixed waters meet, attracting feeding fish and seabirds [46] —although this risk is thought to be small [45].

3.2.3 Research priorities

There is an urgent need for better characterisation of the tidal resource, which includes the interactions of the resource with proposed lagoons and their surrounding environment. Through hydrodynamic modelling, the natural (pre-lagoon) environment needs to be better characterised: wave and storm climates and seasonal/inter-annual variability, residual sediment transport pathways, and turbulent mixing rates, with particular attention paid to potential extreme conditions and climate change.

Numerical models which include a variety of lagoon designs and turbine parameterisation options are being refined [e.g. 44]. Importantly, the shape of the embayment and the number and position of turbines and sluice gates can be optimised to maximise yield and minimise environmental impacts. Future modelling research should, therefore, focus on design optimisation that yields sufficient (rather than maximum) electricity generation, whilst minimising undesirable environmental consequences—especially concerning sediment dynamics and water quality. Models will require repeated bathymetric surveys and time-series wave and current data for validation.

3.3 Wave energy converters

Several model studies have demonstrated significant effects of WECs on the wave climate which, at significant scales of electricity generation, is likely to impact nearshore processes. Although initial work applied constant transmission coefficients across the entire frequency spectrum to simulate energy extraction [47], studies have increasingly incorporated the impacts of WEC power performance [48,49], device size [49], and WEC array configuration [50] on downstream wave propagation.

A concern identified early in the development of WEC technology is the likelihood of coastal erosion patterns to change, impacting beach morphology and shallow water bathymetry in adjacent coastal areas [31,51]. More recently the consideration of WEC arrays for coastal protection purposes has been suggested [52,53], a role which is of increasing importance under climate change-driven future scenarios of coastal flooding and storminess [e.g. 54–56].

Surf zone sandbars reduce sediment erosion on beaches by depth-induced wave breaking [57]; hence, when beach morphology is in equilibrium, this erosion may be balanced by slower onshore migration between storms from lower amplitude dispersed swell waves [57]. Therefore, WECs may alter beach morphology processes [52,53], and research indicates their potential for coastal defence [53].

Future simulation of WEC impact research should continue to address the consideration that WECs do not remove wave power equally across the frequency spectrum. Porter et al. [58] highlight some of the modelling studies that have made efforts to address this issue but note that observational validation is lacking. An additional uncertainty within modelling studies is whether devices will be operational during storm events, as WEC may be switched into 'survival mode' during intense storms to avoid device damage, with the result that a greater proportion of wave energy reduction may occur outside of winter months [50]. The development and implementation of WEC array modules for spectral wave models such as SNL-SWAN [49,58] will prove a useful tool for assessing environmental impacts, particularly when combined with realistic device power transfer functions and wave-current interaction [25,48]. An additional challenge is to increase the ability of morphodynamic models to accurately predict the erosion or accretion/post-storm recovery of beaches [59], The potential impacts of WEC deployments at sites off the Welsh coastline on sand banks and beaches should be considered within the context of our present understanding of the natural variability of such features [60–62].

4. **Potential ecological impacts and research priorities**

4.1 Benthic habitats and species

A primary impact of the construction of Marine Renewable Energy Devices (MREDs) will be the alteration of the benthic habitat within the construction footprint of the device, and any associated cabling routes [63]. However, impacts on the benthic environment are not limited to the physical footprint of devices, as changes in current regimes and associated sediment dynamics have the potential for far field effects such as alteration of food supply, and smothering or increased erosion of sediment [63]. As MREDs scale up from the single device, to the array scale deployments planned around Wales, the potential for habitat fragmentation, a major cause of biodiversity loss within marine environments [64], becomes more relevant. Whilst broad scale habitat knowledge for Welsh coastal areas exists, little is presently known about the finer scale patterns of benthic species distribution within planned MREIs. Future research should take advantage of the emerging ability to use multibeam echosounders for acoustic classification of benthic habitat types within MREIs around Wales.

Potential benefits to benthic biodiversity have also been outlined for MREIs [65]. The main mechanisms for this benefit are: 1) the artificial reef effect [66–68], 2) the ability of MREI sites to function as de-facto marine reserves, where fishing activities such as dredging are excluded [65,69,70]. Device structure and foundations also introduce a hard substrate into areas where it never previously existed. The assemblage of species that artificial structures support, are often different from those occurring on surrounding substrates [71]. In particular, opportunistic species are likely to dominate, and invasive species for which a viable larval supply exists may rapidly colonise the structures [72]. Whilst existing evidence for this comes from Danish windfarms [73], MRED structures in Wales may experience the same effect. Where numerous MREDs are present in the marine environment, the structures may act as stepping-stones for marine invasive species [74]. Of particular concern in Wales is the presence of *Didemnum vexillum* in Holyhead harbour [75,76], and *Crepidula fornicata* in Milford Haven [77], both important areas for boat traffic associated with MREIs in Wales.

4.2 Direct collision and physical interaction

4.2.1 Seabirds

Welsh coastal waters support diverse seabird communities during summer months when large breeding assemblages in the south-west e.g. Grassholm, Skomer, Skokholm and Ramsay Islands [78], exploit waters spanning from the northern Celtic Sea to the northern Irish Sea [e.g. 79–81]. In particular, the populations of Manx shearwaters *Puffinus puffinus*, and northern gannets *Morus bassanus* on Skomer/Skokholm and Grassholm respectively are internationally important. There are also sizeable breeding assemblages spread across Anglesey, and Bardsey Island in the north [78]. In addition, certain regions appear important outside of summer months, most notably southwest Wales for common guillemots *Uria aalge* and lesser-black backed gulls *Larus fuscus* [82]. However, the close proximity of sizeable breeding assemblages in Pembrokeshire, Anglesey and Bardsey Island to areas suitable for tidal stream and wave energy extraction create the possibility of high overlap between distributions of seabirds and array installations [83], and it is during these months when risks are probably higher.

Due to the submerged, or semi-submerged, manner of tidal stream turbines and WEC, these installations are most likely to threaten seabird species during their foraging activities, when species utilise the water column [84]. For submerged tidal stream turbines, any interactions will be constrained to species consistently foraging at depths greater than 5–10m (auks, divers and cormorants) using plunge diving techniques [85]. Due to the dynamic manner of turbine blades at these depths, there is a possibility of negative impacts through collisions [86].For semi-submerged WEC and tidal stream turbines, interactions are also likely among species foraging on the surface and upper water column (gannets, gulls, terns, skuas, shearwaters and storm petrels) using plunge-diving or pecking techniques [85]. Nevertheless, the benign manner of components at these depths mean that risks of negative impacts are probably minimal; instead, some positive impacts may be seen—for example, species have been seen exploiting WEC as novel roosting sites. Therefore, negative impacts associated with physical interactions are most likely to involve pursuit-diving seabirds and moving components of tidal stream turbines, and it is this threat which demands most attention.

As with most taxa, levels of risk probably vary among species. Despite their shared exploitation of high-energy habitats, species generally occupy different microhabitats within these sites [87,88]. Those tending to exploit areas of maximum-energy within these habitats are more likely to encounter devices [89]. The possibility of collisions could then depend upon species' underwater manoeuvrability and speed. The principle differences in diving behaviour occur between wing-propelled auks and foot-propelled cormorants/divers. The use of wings and feet for diving propulsion is considered as a trade-off between speed and manoeuvrability; auks are capable of higher speeds but cormorants/divers exhibit higher manoeuvrability. However, how these differences translate into collision risks remains unknown [84].

The possibility of collisions also depends upon a species' tendency to exploit either benthic or pelagic prey, with the former associated with deeper, lengthier and riskier dives [86]. Levels of risk also vary within a species over space and time—for instance, species' tendency to exploit areas of maximum energy, and therefore interact with installations, could vary seasonally due to differences in their core foraging strategies, or migratory movements from inshore into offshore habitats during non-breeding seasons [88]. Consistent differences in foraging strategies among sites, perhaps linked with local resource availability or 'behavioural cultures', could further determine a species' likelihood of interacting with devices. In one such example, cormorant species exploit areas of relatively low energy within some sites, but areas of maximum energy within others [88,90,91]. In addition to differences among and within species, levels of risk almost certainly vary among devices depending on their specifications, Potential risk from tidal kites, for instance, would probably vary greatly from conventional tidal stream turbine designs due to their fundamental differences in design and operational dynamics.

The aforementioned variations in levels of risk create a need to understand behaviours at a species, seasonal and site-specific level. Quantifying a species' relative use of a high-energy site, and then use of areas suitable for installations within the site, forms one component of risk assessment [89]. Use of existing at-sea aerial/vessel surveys over appropriate regions, in conjunction with targeted surveys within the focal site, can help address these questions [89]. Quantifying foraging behaviours immediately around devices is another component of risk assessment. Recording such behaviours provides challenges due to the inherent difficulties in recording fine resolution behavioural information within very specific locations, particularly in the demanding conditions within high-energy sites [89]. This explains why the influence of diving behaviour on collision risk remains largely unknown [84]. However, novel technologies using sub-surface hydroacoustic methods alongside devices are overcoming these issues [92]. What is clear, however, is that there are large differences between tidal/wave and offshore wind electricity generation concerning the spatial extent and resolution of data needed to assess potential impacts on seabirds. The need for high-resolution data at fine spatial scales within relatively small sites means that targeted and novel approaches are needed, rather than a simple adaption of surveying techniques commonly used for offshore wind covering much larger scales and areas.

4.2.2 Fish

Within the UK, migratory fish have been highlighted as the main concern in regards to fish interactions with MREDs [93]. However, various fish species also contribute to the diet of diving seabirds and marine mammals, and so are linked to top-predators that are identified as potentially vulnerable to MREDs. Physical injuries to fish caused by mechanical strike, shear and cavitation are the principle risks identified [94,95]. These potential impacts are shared by most tidal turbine technologies but the risk will differ between ‘open ocean’ tidal stream turbines, and those that are within an enclosing structure in a tidal range development or WEC. Tidal kite projects will also have broadly similar potential impacts but may be higher risk due to the kite device moving through the water at several times the ambient current velocity [96]. WECs are considered to be of comparatively lower concern based on designs presently proposed [97], but will need to be evaluated for each specific design proposed for deployment and how potential fish aggregation may modify any collision risk with marine mammals and diving seabirds. Designs may cause avoidance due to device movement and associated noise, or alternatively some surface floating devices may function as *de-facto* fish aggregating devices [98].

Preliminary studies on horizontal axis turbines indicate that fish are able to avoid turbines with higher avoidance rates when fish are in schools and during the day, due to social behaviour and visual avoidance [99]. However, within three metres of a turbine avoidance was low, with only 1% of fish observed not passing through the turbines [99]. A major concern surrounding tidal lagoons is therefore fish impacts, which may not easily bypass the turbines within the lagoon wall. Efforts to minimise this risk require thorough consideration of device design [13]. For example, it has been suggested that large-diameter turbines, with slower rotor speeds than small-diameter turbines, are likely to be less hazardous to fish [100]. In addition, two-way generation turbines have been suggested to minimise environmental impact [20], and fish passes for migratory fish could be incorporated into MREDs [45].

Fish species composition and abundance vary spatially between different tidal stream project sites, and temporally over seasonal or diurnal cycles, which means site specific studies with control sites monitored over an appropriate timescale are necessary to assess potential device impact. The potential interactions between fish and tidal turbines have been identified as a research gap for tidal stream power generation in the UK as a whole, and Wales in particular [86,101]. Gaining a more thorough understanding of the ecological function of high tidal current areas and those surrounding tidal lagoons for fish species in Welsh coastal areas is necessary before potential impacts can be fully understood and mitigated appropriately.

Effective methodologies to study fish interactions with wave and tidal devices are still being developed. Both static and mobile acoustic surveys have been employed at locations in North America, together with acoustic tagging and video methods at some sites [99,102]. Acoustic transmitting tags may provide information on the broader spatial dynamics and migration routes of fish species whose ranges intersect with the proposed MREI sites around Wales. Moored devices that collect data on the presence and behaviour of fish and plankton, in addition to ambient noise before, during, and after construction are likely to be useful tools, not least due to the difficulties of conducting regular boat based observations in high-energy environments.

4.2.3 Marine Mammals

Welsh coastal waters support a number of marine mammal species including both resident and transient populations. Eighteen species have been recorded since the 1990s, and five of these are commonly encountered [103]. The extent of collision risk with marine mammals is currently unclear and it is likely to be species and site-specific, and further influenced by device design. Turbines used in tidal stream and range technology are likely to pose more of a risk than WECs. However, fast-moving animals that surface regularly could be vulnerable to collision or entrapment from WECs.

Present knowledge of collision risk is limited and focuses on modelling the encounter rate between marine mammals and turbines based on physical characteristics of turbines, physical and behavioural characteristics of animals and local density estimates [86]. However, in many cases, validated input parameters are not available and therefore the accuracy of the model is uncertain. As part of recent developments at MRED test sites, mitigation procedures including using active sonar to detect mammals and an initial shut down clause when mammals were in close proximity were in place during device operation [71,104].

The first tidal turbine in Wales has been installed in Ramsey Sound, Pembrokeshire. Mitigation measures during operation will include the use of active sonar, marine mammal observers and passive acoustics for tracking the fine scale underwater movements of mammals around tidal devices [105]. As so few MREDs are in operation, opportunities to collect empirical data on marine mammal impacts are limited. In Wales, where a number of MREDs are in the planning stages, there is an opportunity to focus efforts in collecting pre-construction site-specific baseline data relevant to assessing the risk of impacts. To refine assessments of collision likelihood, finer-scale studies into the distribution (both horizontal and vertical) of marine mammals within sites are required, focussing on how distribution and density vary with current speeds and in relation to site physical features.

High-energy areas are challenging field sites to study marine mammals due to turbulence, strong currents and noise. In some cases traditional research methods should be adapted to better suit the difficult nature of these locations, such as developing streamlined housings for moored acoustic recorders [e.g. 106], or drifting devices [107] to reduce current noise. During vessel-based surveys it may be necessary to alter transect design to reduce the bias of strong current direction affecting speed over ground [107,108].

There are further challenges relating to collecting fine-scale data such as the availability of associated data collected at the required scale and the spatial precision of locating animals. Regarding the latter, hydrophone arrays capable of tracking echolocating animals in 3D may be suitable [108]. Recent advancements have also been made to design arrays that will function better in high-energy environments and with relatively low cost [109].

Visual methods can be useful for some species, such as baleen whales, which do not echolocate. Some odontocetes may not vocalise as frequently or may be easier to detect visually compared with other species such as harbour porpoise (*Phocoena phocoena*). Many development locations, including tidal lagoons and near-shore tidal stream sites may be well suited to land-based visual surveys. A long-term dataset exists from land-based watches at Ramsey Sound [110], and at the tidal stream site at the Skerries, a pioneering method is being developed to calculate absolute density estimates from the coastline.

It is also vital to assess population effects of collisions with MREDs which may occur in Welsh waters. However, without robust density estimates relative to the development site it’s not possible to predict the consequences of fatal collisions on a population. Traditionally, density estimates have been calculated using a distance sampling protocol, particularly vessel-based line-transect surveys. In recent years, the technology of passive acoustic arrays to estimate density has been developed, however, there are difficulties associated with obtaining density estimates with sufficient power to detect trends for highly mobile species in relatively small areas such as the Welsh Tide and Wave Demonstration Zones.

4.3 Noise and electromagnetic field effects

There is growing awareness of the potential impacts of anthropogenic underwater noise on the marine environment, as the role of sound in the life cycles of key marine organisms is increasingly apparent [e.g. 111,112]. The generation of underwater noise is common to all of the forms of MRED envisaged along the Welsh coastline. In particular, the construction phases will share the features of increased boat traffic, and the noise and vibrations generated during device installation. For tidal range technology the construction phase will be extensive and is likely to constitute a more chronic disturbance than the shorter duration high intensity activities, particularly pile driving, which will be required for several forms of tidal stream and wave energy devices. During operation, underwater noise will be generated by tidal turbines, and by some wave energy converters, however potential impacts may be reduced due to the ambient noise levels in high current areas such as the West Anglesey Tidal Demonstration Zone, which tend to be elevated due to fast flowing water and sediment movement. Conversely, if noise levels generated during MRED operation are low, mobile species may not be alerted to the risk of collision until close proximity to a MRED.

Anthropogenic noise is a particular concern for cetaceans, given their noise sensitivity associated with employing a wide band of acoustic frequencies for navigation, communication and foraging. A key issue is whether exposure to noise results in behavioural changes causing displacement from key habitats or disturbance at breeding or social activity sites that will affect cetacean populations in the long-term [111]. Initial studies investigating generation of noise by wave and tidal devices suggest that displacement effects may be small or unlikely due to the low received levels in comparison with ambient noise [104,113]. However, these are specific to single devices and there is a requirement to consider scaled up effects relating to commercial-scale arrays.

Whilst primarily concentrating MRED deployment within Demonstration Zones around Wales may be beneficial in reducing the spatial extent of noise disturbance, a research challenge is determining if potential avoidance of these sites by large mobile species translates into population level impacts. Behavioural studies, encompassing both observational and active behavioural response can reveal reactions to a disturbance. This becomes highly useful if links can be made between behavioural change and individual health, allowing these findings to be modelled into population consequences [114,115]. In some cases no behavioural response will be observed, however, this does not necessarily mean an absence of disturbance capable of influencing survival. Similarly, a behavioural change may indeed be recorded but which has no significant consequences relating to the health of the individual [114,115], therefore, establishing the links between behaviour and effects on survival and fecundity should be a research priority.

Electromagnetic field (EMF) emissions along cabling routes are an additional consideration for tidal stream and wave energy sites around the coast of Wales. Proposed tidal lagoon developments will not require electricity to be transported from offshore locations, as the current proposals are that the cable route will run underneath the lagoon boundary, with EMF emissions calculated as ~100μT at the breakwater surface [116]. Due to the rapid reduction in EMF strength with distance in water, emissions will rapidly fall to background levels [~50μT: 117], and any potential impact will be localised to the lagoon breakwater.

EMF emissions can be detected by a variety of marine life, but fish species which use magnetic fields for orientation, and the electrosensitive elasmobranchs are most vulnerable to disturbance [118]. A UK-wide concern for diadromous fish species is the potential for migration routes to be disrupted where these interact with cabling routes [119]. For Wales, migratory stocks of the European eel (*Anguilla Anguilla*), Sea Trout (*Salmo trutta L*), and Salmon (*Salmo salar*) may interact with proposed cabling routes and tidal lagoons structures [120–122] .

Whilst existing evidence for the impacts of EMF produced by cabling on fish distributions comes from offshore wind farm sites [e.g. 123], comparable cabling specifications and deployment methods will be utilised in offshore wave or tidal installations. Recent studies have noted that research to determine the potential impacts of cabling on elasmobranches is lacking at existing UK wave energy sites

[69], and have further suggested the potential for strategic management of MREI with respect to their possible impacts on elasmobranchs for some areas of the UK [124]. An issue that requires further research within both Welsh and broader UK waters is the potential for cumulative developments to create barriers to migration or usage of areas with important functioning to elasmobranch populations. Research in North Wales will focus on the Holyhead Deep, off the west coast of Anglesey, an area targeted by recreational anglers for elasmobranchs, in particular the UK priority species Tope (*Galeorhinus galeus*), and also an area where TEC device deployment is planned.

5. Water quality impacts

MREI installed in the marine environment will primarily alter water quality through the introduction of new contaminants or the re-mobilisation of existing contaminants. The extent of these environmental effects will depend on device characteristics, alterations to the local hydrodynamic regime, site geomorphology, and the marine species present within the site. Both near and far-field water quality issues may result from MREI, but are likely to be highly site specific [18,125,126].

5.1 Construction and decommissioning phases

The deployment of MRED requires usage of a range of compounds to enable devices to function in the harsh maritime environment, for example gearbox lubricants, anti-corrosion coatings, and anti-fouling paints [127]. Experiments carried out in laboratory settings with some of the chemicals within these compounds have demonstrated detrimental impacts on marine biota, and whilst low concentrations of such chemicals are unlikely to induce mortality, there is potential for sub-lethal effects on the sensory systems, growth and behaviour of marine species [128]. Over longer timescales low concentrations could result in the bioaccumulation of toxins including heavy metals in sediments surrounding MREI, and ultimately throughout the marine food web [129]. Over shorter timescales the increased boat traffic associated with device installation poses a risk to water quality due to small, potentially frequent fuel leakages. Larger, infrequent releases of chemicals used for maintenance may occur due to accidents or spillages, resulting in localised behavioural or toxicity impacts to marine biota [129].

Potential impacts resulting from the installation phase also need to consider the subsea cabling required to bring electricity onshore. The techniques presently employed to bury subsea cabling cause sediment re-suspension and consequently, any contaminated sediments will be locally re-mobilised, and dependant on sediment size and hydrodynamic regime, may be transported further afield. A decommissioning phase that includes the removal of subsea cabling will again disturb any sediment in the surrounding area; contaminants that have accumulated along the cabling pathway will be re-mobilised. Device decommissioning may also cause water quality issues if toxins are released from compounds contained within the device structure e.g. the lubricants and hydraulic fluids used in gearboxes, bearings and rotor shafts.

5.2 Contaminant and water quality issues during operation

Tidal energy devices alter the hydrodynamic regime at the installation site; in sites with fine sediments, increases in water turbulence may lead to localised increases in turbidity. In areas with existing sediment contamination, increased turbidity is likely to lead to contaminant re-suspension. The altered hydrodynamic regime will influence the spatial scale of the impacts from re-suspended contaminants, devices located offshore are at less risk since contamination reduces with increasing distance from the shore, due to greater dilution capacity in the open ocean [130]. In comparison, devices near shore, in areas where fine sediment deposition occurs and land based sources of contaminants are more common, pose a greater risk of contributing to and remobilizing contaminated sediments.

Tidal energy harvested through the impoundment of water in a tidal lagoon impoundments operation has high potential for water contamination issues, dependent on the location of the lagoon development. If the area enclosed by a lagoon already receives contamination from different sources, impounding the water for part of the tidal cycle will cause changes to the tidal and residual flows. The amount of water in circulation will be reduced when the tidal flows and therefore flushing rates are reduced. With reduced resuspension the levels of suspended particulate matter will drop, resulting in deposition of both fine sediment and any associated chemical contaminants. This will lead to increased light penetration and accumulation of contaminants in the sediments which could create or exacerbate existing water quality concerns, such as the eutrophication and hypoxia associated with excessive effluent retention [45].

Water column stratification is likely to be altered within the lagoon, affecting seawater temperature; this will influence seasonal biological processes (e.g. phytoplankton growth). This could lead to an increase in phytoplankton blooms, which can be harmful to both marine biota and humans, causing a range of deleterious physiological and environmental effects [131]. Certain harmful algae (HA; e.g. *Dinophysis*) produce potent natural toxins that are concentrated by filter feeders and passed through the food chain causing adverse affects on a variety of marine organisms, and shellfish poisoning if consumed by humans [132,133]. Other HA are non-toxic but attain high biomass levels which reduces the biodiversity of the phytoplankton community structure and the amount of light reaching the benthos, limiting the growth of photosynthetic species and the hunting activities of piscivorous species [131,134–136]. The decomposition of blooms can lead to reductions in dissolved oxygen concentrations which in turn will effect the biodiversity of the area [137].

5.3 Research priorities

There is a need to utilise a multidisciplinary approach in assessing potential contaminant issues, including hydrodynamic and sediment transport modelling to enable a greater understanding of the fate of contaminants, thereby increasing certainty surrounding the magnitude of impacts contaminants may cause. Conducting robust baseline studies to distinguish between current and future impacts as part of any research design is imperative. More detailed research investigating the toxic properties of the chemicals used to maintain the devices and the long-term effects of these to marine species should be carried out. This should be carried out concurrently with further development of non-toxic alternative materials. In the case of tidal lagoons, research needs to be undertaken to better understand the effects of enclosing contaminants within an embayment. There is a need to model contaminant fluxes under different scenarios when the lagoon is in place and calculate how much flushing will occur through the turbines to enable the industry to understand the environmental consequences of impounding the coastline. This research should include different scenarios (e.g. flood events, storm surges), at different times of the year and at different states of the tide to fully understand contaminant levels within a range of environmental conditions. Finally, research is needed to develop the potential to mitigate water quality issues: by identifying the main contributing sources and the transport mechanisms work can be undertaken to find and test appropriate bioremediators in these environments.

6. **Socio-economic impacts and research priorities**

A significant knowledge gap in the development of offshore wave and tidal installations is the paucity of rigorous social science research to provide an evidence base about the perceptions, attitudes and opinions of local communities at both an individual and community levels, and at local, regional and national spatial scales. Much of the social science surrounding renewable energy installations conducted to date has focussed on wind power, since these technologies are at a more advanced stage of development than wave or tide. Whilst it is likely that there will be some similarities between attitudes towards wind farms and wave and tidal electricity generation, as yet this assumption is unproven. The importance of fully understanding the social attitudes surrounding renewable energy installations is vital if negative public attitudes toward such developments are to be avoided.

Public attitudes towards electricity generation are complex and made up of interrelated trade-offs that change across both place and time [138], and are influenced by a person's underlying values and beliefs [139]. Energy installations have a long history of being affected by changing public attitudes; the visual and auditory disturbances as a result of wind power installations have been found to affect individual's quality of life [140], and the impact on the landscape has led to organisations such as Scottish National Heritage issuing guidance on siting wind farms [141]. The effects of public opinion on energy industries can be catastrophic, for example Japan has curtailed its nuclear program and is now exploring alternative energy options as a result of wide-spread public mistrust in nuclear energy following the Fukoshima disaster [142]. It is clear that public opinion is intrinsic to the successful deployment of large-scale energy developments and without a thorough understanding of the likely social and economic impact upon communities in close proximity to potential wave and tidal installations, it is impossible to develop strategies to ensure public acceptability. The economic incentives for developers to progress technical capabilities in this arena will be curtailed should public opinion be misunderstood or poorly accounted for; conversely, direct consumer benefits (for example through reduced energy bills) is unlikely and must be made clear.

Economic benefits are often used to encourage the development of renewable energies and this has certainly been the case in the development of wave and tidal resources in the UK. At the country scale, Wales will benefit from developing its wave and tidal resource, but whether benefits will filter down to the regional and local scale will depend on local and regional abilities to provide the goods and services that developers require. Fanning et al. [143] estimate that during the development and installation phase, total expenditure leakage outside of Wales would be 35% for tidal and 50% for wave. However, regional opportunities from installation and maintenance aspects of marine renewable energy development do exist, with employment estimates of between 35.3 and 22.9 full-time equivalent jobs (FTE) per MW for tidal energy developments, and between 32.3 and 26.4 FTE per MW for wave developments [143].

Such employment and economic opportunities do depend on appropriate strategic plans being in place, for example to offer qualifications that allow employment opportunities to be taken up by communities local to the development. Equally, employment opportunities during the construction phase are not permanent jobs; inevitably the labour force retracts when the installations are operational and employees may be forced to re-locate from site to site. Furthermore, the development of Wales's marine energy resources may conflict with existing Welsh economic activities, for example fisheries and tourism. Overall, the marine environment of Wales is reported to produce an income of £6.8 billion and generate £2.5 billion in GDP [144], whilst the fisheries sector within Wales has been valued at £105.4 million and estimated to provide 1,659 FTE jobs [145]. An effective and scientifically robust strategic overview of marine spatial planning in Wales is necessary to ensure that conflicts between different uses of the marine environment are minimised, and equitably divided where conflicts are unavoidable. These considerations are timely, as the Welsh National Marine Plan being prepared by the Welsh Government is currently in draft stage, and the need for widespread consultation within this process has been recognised [146].

Clearly, the social and economic drivers behind marine renewable developments are linked; care must be taken that both are considered in a strategic evaluation of how Wales chooses to develop its marine resource. Initial findings from research undertaken by the SEACAMS project indicates key knowledge gaps that should be addressed in relation to the development of wave and tidal energies from a social science perspective. Firstly, to understand how wave and tidal energy developments are likely to impact levels of place attachment (i.e. the emotional or affective bond between people and valued places). Aquatic environment are valued environments [147], and despite the perception that wind and tidal devices are predominantly below sea level and therefore 'invisible', there are associated on-shore infrastructure needed, for example connections to the National Grid. Although MREIs can provide important recreational opportunities, they also have the potential to disrupt local communities sense of what is unique about their landscape [148]. Whilst the benefits of developments are often focussed on employment opportunities, research has shown that communities can be sceptical about whether local people have the skills needed; moreover, in communities with strong place attachment, the promise of employment is not enough to override concerns relating to the visual impact any development would have on the landscape [148]. Additionally, no-take zones or exclusion zones in areas where fisheries play a key role in the local economy are likely to prove contentious and may limit the wide-scale roll out of MREIs [149].

Conversely, in communities where renewable energy developments result in direct community benefits, for example through reduced energy prices or land rental revenue, acceptability has been shown to be higher [150–152], but little research has documented the limits of this relationship, or expanded this to cover the role of wave and tidal energy development. Other potential benefits, such as coastal and flood protection (in the case of tidal lagoons), the provision of amenity opportunities, or the creation of additional marine habitats may positively influence local communities. Finally, the role of trust, faith and fairness in both the development process and the siting process have been shown to influence acceptability of renewable energy developments [153–155]. Determining how these factors relate to wave and tidal energy developments will allow more effective public engagement opportunities, potentially reduce conflict, and lead to realistic expectations for both local communities and developers.

7. Conclusions

The marine renewable energy industry is at a critical stage of development in Wales, as the wave and tidal demonstration zones begin to fulfill their role as device testing locations, and some developments move from the tests device to the small array stage. The research challenges presented are common to those facing many countries with the potential for the implementation of several marine renewable energy technologies (Table 1). Determination of the optimum siting for devices in relation to the resource is a priority for developers, whilst, at broader spatial scales, physical and ecological impacts and the relationships with grid connections are important policy and consenting considerations. In addition, societal attitudes towards marine renewable energy will continue to evolve as developments progress and social and economic impacts become clearer.

Appropriate design and management measures will maximize positive influences of MREIs on local biodiversity and the marine environment. For instance, as the designation of additional marine protected areas is planned for Wales, consideration should be given to the potential for both conflict and synergy between MPAs and MREIs.

Ongoing research will reduce uncertainty in the estimation of impacts from MREIs, and assist in reducing the risks to developers. There is currently an opportunity to collect baseline data within appropriately designed studies to facilitate assessment of impacts following device installation at Welsh Demonstration Zones. However, prior to installation, a combination of modeling studies and conducting research on existing artificial structures in the marine environment offers the best potential to predict the effects of MREIs.

Figure Captions:

Figure 1. Locations of marine renewable energy development and test sites around Wales: a) tidal stream sites, including the West Anglesey Tidal Demonstration Zone, b) tidal lagoon sites, c) wave power sites, including the South Pembrokeshire Wave

Demonstration Zone, d) main electricity grid connections around the coastline of Wales.

Figure 2. Sites of environmental conservation importance around the Welsh coastline: a) protected area which are primarily land-based, but which extend into the coastal environment, b) protected areas with a marine focus, c) indicative boundaries of newly proposed marine protected areas which are under consideration.

Figure 3. The tidal energy resource of the Irish Sea. Tidal range resource is shown in panel (a), as the mean spring tide amplitude in metres with lines of co-phase in hours, relative to the port of Holyhead (red circle of panel a). The tidal-stream resource is shown in panel (b), as the major axis of peak spring tidal ellipse (M2 and S2 in m/s) with lines of co-phase in hours relative to the Anglesey tidal-stream energy demonstration zone (red circle of panel b). Both the tidal range and tidal-stream energy resource maps (a and b respectively) are calculated using hourly data from the well validated high-resolution 3D ROMS tidal model of [5].

Figure 4. Simulated annual mean (2014) wave power in the Irish Sea, based on the SWAN wave model and ERA-Interim wind fields. The model is nested within an outer SWAN model of the North Atlantic [33].

Table 1. Summary of research challenges within Welsh Marine Renewable Energy Developments.

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7. References

[1] HM Government, The UK low carbon transition plan: national strategy for climate and energy, HM Government, London, 2009.

[2] HM Government, The carbon plan: delivering our low carbon future, HM Government, 2011.

[3] The Crown Estate, UK wave and tidal key resource areas report, The Crown Estate, 2012.

[4] DECC, Digest of United Kingdom Energy Statistics, Department of Energy and Climate Change, London, 2015.

[5] M. Lewis, S.P. Neill, P.E. Robins, M.R. Hashemi, Resource assessment for future generations of tidal-stream energy arrays, Energy. 83 (2015) 403–415. doi:10.1016/j.energy.2015.02.038.

[6] WG, A low carbon revolution - The Welsh Assembly Government energy policy statement, Welsh Government, 2010.

[7] S.P. Neill, J.R. Jordan, S.J. Couch, Impact of tidal energy converter (TEC) arrays on the dynamics of headland sand banks, Renewable Energy. 37 (2012) 387–397. doi:10.1016/j.renene.2011.07.003.

[8] S.P. Neill, M.R. Hashemi, M.J. Lewis, Tidal energy leasing and tidal phasing, Renewable Energy. 85 (2016) 580–587. doi:10.1016/j.renene.2015.07.016.

[9] F.O. Rourke, F. Boyle, A. Reynolds, Marine current energy devices: Current status and possible future applications in Ireland, Renewable and Sustainable Energy Reviews. 14 (2010) 1026–1036. doi:10.1016/j.rser.2009.11.012.

[10] R. Martin-Short, J. Hill, S.C. Kramer, A. Avdis, P.A. Allison, M.D. Piggott, Tidal resource extraction in the Pentland Firth, UK: Potential impacts on flow regime and sediment transport in the Inner Sound of Stroma, Renewable Energy. 76 (2015) 596–607. doi:10.1016/j.renene.2014.11.079.

[11] V. Ramos, R. Carballo, M. Álvarez, M. Sánchez, G. Iglesias, Assessment of the impacts of tidal stream energy through high-resolution numerical modeling, Energy. 61 (2013) 541–554. doi:10.1016/j.energy.2013.08.051.

[12] R. Burrows, I.A. Walkington, N.C. Yates, T.S. Hedges, J. Wolf, J. Holt, The tidal range energy potential of the West Coast of the United Kingdom, Applied Ocean Research. 31 (2009) 229–238. doi:10.1016/j.apor.2009.10.002.

[13] A. Angeloudis, R. Ahmadian, R. Falconer, Combined potential and impacts of tidal lagoons along the North Wales coast, in: IAHR World Congress, 2015.

[14] R.A. Falconer, X. JunQiang, L. BinLiang, R. Ahmadian, The Severn Barrage and other tidal energy options: Hydrodynamic and power output modelling, Science in China Series E-Technological Sciences. 52 (2009) 3413–3424. doi:10.1007/s11431-009-0366-z.

[15] B. Lin, R. Ahmadian, R. Falconer, Hydro-environmental modeling of proposed Severn barrage, UK, in: Proceedings of the ICE - Energy, 2010: pp. 107–117. doi:10.1680/ener.2010.163.3.107.

[16] J. Xia, R.A. Falconer, B. Lin, Hydrodynamic impact of a tidal barrage in the

Severn Estuary, UK, Renewable Energy. 35 (2010) 1455–1468. doi:10.1016/j.renene.2009.12.009.
[17] J. Xia, R.A. Falconer, B. Lin, Impact of different operating modes for a Severn Barrage on the tidal power and flood inundation in the Severn Estuary, UK, Applied Energy. 87 (2010) 2374–2391. doi:10.1016/j.apenergy.2009.11.024.
[18] M. Kadiri, R. Ahmadian, B. Bockelmann-Evans, W. Rauen, R. Falconer, A review of the potential water quality impacts of tidal renewable energy systems, Renewable and Sustainable Energy Reviews. 16 (2012) 329–341. doi:10.1016/j.rser.2011.07.160.
[19] J. Zhou, S. Pan, R.A. Falconer, Effects of open boundary location on the far-field hydrodynamics of a Severn Barrage, Ocean Modelling. 73 (2014) 19–29. doi:10.1016/j.ocemod.2013.10.006.
[20] J. Zhou, S. Pan, R.A. Falconer, Optimization modelling of the impacts of a Severn Barrage for a two-way generation scheme using a Continental Shelf model, Renewable Energy. 72 (2014) 415–427. doi:10.1016/j.renene.2014.07.036.
[21] J. Zhou, R.A. Falconer, B. Lin, Refinements to the EFDC model for predicting the hydro-environmental impacts of a barrage across the Severn Estuary, Renewable Energy. 62 (2014) 490–505. doi:10.1016/j.renene.2013.08.012.
[22] T.L. Shaw, R. Kirby, Severn Barrage, UK—environmental reappraisal, Proceedings of the ICE - Engineering Sustainability. 158 (2005) 31–39. doi:10.1680/ensu.2005.158.1.31.
[23] C.S. Russell, Environmental Appraisal of Severn Barrage, Marine Policy. 2 (1978) 72–74.
[24] DECC, Severn Tidal Power, HM Government, London, 2010.
[25] M.J. Lewis, S.P. Neill, M.R. Hashemi, M. Reza, Realistic wave conditions and their influence on quantifying the tidal stream energy resource, Applied Energy. 136 (2014) 495–508. doi:10.1016/j.apenergy.2014.09.061.
[26] A.C. Baker, J. Walbancke, P. Leache, Tidal lagoon power generation scheme in Swansea Bay, Welsh Development Agency, 2006.
[27] I. Fairley, P. Evans, C. Wooldridge, M. Willis, I. Masters, Evaluation of tidal stream resource in a potential array area via direct measurements, Renewable Energy. 57 (2013) 70–78. doi:10.1016/j.renene.2013.01.024.
[28] Tidal Lagoon Swansea Bay plc, Stakeholder Newsletter No 15, Tidal Lagoon Swansea Bay, 2015.
[29] A. Angeloudis, R. Ahmadian, R.A. Falconer, B. Bockelmann-Evans, Numerical model simulations for optimisation of tidal lagoon schemes, Applied Energy. 165 (2016) 522–536.
[30] K. Gunn, C. Stock-Williams, Quantifying the global wave power resource, Renewable Energy. 44 (2012) 296–304. doi:10.1016/j.renene.2012.01.101.
[31] A. Clément, P. McCullen, A. Falcão, A. Fiorentino, F. Gardner, K. Hammarlund, G. Lemonis, T. Lewis, K. Nielsen, S. Petroncini, M.T. Pontes, P. Schild, B.O. Sjostrom, H.C. Sorensen, T. Thorpe, Wave energy in Europe: current status and perspectives, Renewable and Sustainable Energy Reviews. 6 (2002) 405–431.
[32] F.O. Rourke, F. Boyle, A. Reynolds, Renewable energy resources and technologies applicable to Ireland, Renewable and Sustainable Energy Reviews. 13 (2009) 1975–1984. doi:10.1016/j.rser.2009.01.014.
[33] S.P. Neill, M.R. Hashemi, Wave power variability over the northwest European shelf seas, Applied Energy. 106 (2013) 31–46.

doi:10.1016/j.apenergy.2013.01.026.

[34] J. Falnes, A review of wave-energy extraction, Marine Structures. 20 (2007) 185–201. doi:10.1016/j.marstruc.2007.09.001.

[35] A.F. de O. Falcão, Wave energy utilization: A review of the technologies, Renewable and Sustainable Energy Reviews. 14 (2010) 899–918. doi:10.1016/j.rser.2009.11.003.

[36] G. Iglesias, R. Carballo, Offshore and inshore wave energy assessment: Asturias (N Spain), Energy. 35 (2010) 1964–1972. doi:10.1016/j.energy.2010.01.011.

[37] R. Carballo, G. Iglesias, A methodology to determine the power performance of wave energy converters at a particular coastal location, Energy Conversion and Management. 61 (2012) 8–18. doi:10.1016/j.enconman.2012.03.008.

[38] G. Sutherland, M. Foreman, C. Garrett, Tidal current energy assessment for Johnstone Strait, Vancouver Island, Proceedings of the Institution of Mechanical Engineers, Part a: Journal of Power and Energy. 221 (2007) 147–157. doi:10.1243/09576509JPE338.

[39] S.P. Neill, E.J. Litt, S.J. Couch, A.G. Davies, The impact of tidal stream turbines on large-scale sediment dynamics, Renewable Energy. 34 (2009) 2803–2812. doi:10.1016/j.renene.2009.06.015.

[40] T. Blackmore, W.M.J. Batten, A.S. Bahaj, Influence of turbulence on the wake of a marine current turbine simulator, Proceedings of the Royal Society a: Mathematical, Physical and Engineering Sciences. 470 (2014) 20140331–20140331. doi:10.1098/rsta.2012.0196.

[41] T.J. Dolphin, C.E. Vincent, C. Coughlan, J.M. Rees, Variability in Sandbank Behaviour at Decadal and Annual Time-Scales and Implications for Adjacent Beaches, J Coastal Res. (2007) 731–737.

[42] P.E. Robins, S.P. Neill, M.J. Lewis, Impact of tidal-stream arrays in relation to the natural variability of sedimentary processes, Renewable Energy. 72 (2014) 311–321. doi:10.1016/j.renene.2014.07.037.

[43] R. Ahmadian, R. Falconer, B. Bockelmann-Evans, Far-field modelling of the hydro-environmental impact of tidal stream turbines, Renewable Energy. 38 (2012) 107–116. doi:10.1016/j.renene.2011.07.005.

[44] A. Cornett, J. Cousineau, I. Nistor, Assessment of hydrodynamic impacts from tidal power lagoons in the Bay of Fundy, International Journal of Marine Energy. 1 (2013) 33–54.

[45] J. Wolf, I.A. Walkington, J. Holt, R. Burrows, Environmental impacts of tidal power schemes, Proceedings of the Institution of Civil Engineers-Maritime Engineering. 162 (2009) 165–177. doi:10.1680/maen.2009.162.4.165.

[46] A.E. Hill, J. Brown, L. Fernand, The western Irish Sea gyre: A retention system for Norway lobster (Nephrops norvegicus)? Oceanologica Acta. 19 (1996) 357–368.

[47] D.L. Millar, H.C.M. Smith, D.E. Reeve, Modelling analysis of the sensitivity of shoreline change to a wave farm, Ocean Engineering. 34 (2007) 884–901. doi:10.1016/j.oceaneng.2005.12.014.

[48] H.C.M. Smith, C. Pearce, D.L. Millar, Further analysis of change in nearshore wave climate due to an offshore wave farm: An enhanced case study for the Wave Hub site, Renewable Energy. 40 (2012) 51–64. doi:10.1016/j.renene.2011.09.003.

[49] G. Chang, K. Ruehl, C.A. Jones, J. Roberts, C. Chartrand, Numerical modeling of the effects of wave energy converter characteristics on

nearshore wave conditions, Renewable Energy. 89 (2016) 636–648. doi:10.1016/j.renene.2015.12.048.

[50] A. Palha, L. Mendes, C.J. Fortes, A. Brito-Melo, A. Sarmento, The impact of wave energy farms in the shoreline wave climate: Portuguese pilot zone case study using Pelamis energy wave devices, Renewable Energy. 35 (2010) 62–77. doi:10.1016/j.renene.2009.05.025.

[51] O. Defeo, A. McLachlan, D.S. Schoeman, T.A. Schlacher, J. Dugan, A. Jones, M. Lastra, F. Scapini, Threats to sandy beach ecosystems: A review, Estuar Coast Shelf S. 81 (2009) 1–12. doi:10.1016/j.ecss.2008.09.022.

[52] J. Abanades, D. Greaves, G. Iglesias, Coastal defence through wave farms, Coastal Engineering. 91 (2014) 299–307. doi:10.1016/j.coastaleng.2014.06.009.

[53] E. Mendoza, R. Silva, B. Zanuttigh, E. Angelelli, T.L. Andersen, L. Martinelli, J.Q.H. Norgaard, P. Ruol, Beach response to wave energy converter farms acting as coastal defence, Coastal Engineering. 87 (2014) 97–111. doi:10.1016/j.coastaleng.2013.10.018.

[54] S. Temmerman, P. Meire, T.J. Bouma, P.M.J. Herman, T. Ysebaert, H.J. De Vriend, Ecosystem-based coastal defence in the face of global change, Nature. 504 (2013) 79–83. doi:10.1038/nature12859.

[55] F. Feser, M. Barcikowska, O. Krueger, F. Schenk, R. Weisse, L. Xia, Storminess over the North Atlantic and northwestern Europe - A review, Quarterly Journal of the Royal Meteorological Society. 141 (2015) 350–382. doi:10.1002/qj.2364.

[56] M. Lewis, K. Horsburgh, P. Bates, R. Smith, Quantifying the Uncertainty in Future Coastal Flood Risk Estimates for the U.K, J Coastal Res. 27 (2011) 870–881.

[57] F. Hoefel, Wave-Induced Sediment Transport and Sandbar Migration, Science. 299 (2003) 1885–1887. doi:10.1126/science.1081448.

[58] A. Porter, K. Ruehl, C. Chartrand, Further Development of SNL-SWAN, A validated wave energy converter array modeling tool, 2nd Marine Energy Technology Symposium, 2014.

[59] T. Prime, J.M. Brown, A.J. Plater, Flood inundation uncertainty: The case of a 0.5% annual probability flood event, Environmental Science & Policy. 59 (2016) 1–9.

[60] M.J. Lewis, S.P. Neill, A.J. Elliott, Interannual Variability of Two Offshore Sand Banks in a Region of Extreme Tidal Range, J Coastal Res. 300 (2015) 265–275. doi:10.2112/JCOASTRES-D-14-00010.1.

[61] T. Schmitt, N.C. Mitchell, Dune-associated sand fluxes at the nearshore termination of a banner sand bank (Helwick Sands, Bristol Channel), Continental Shelf Research. 76 (2014) 64–74. doi:10.1016/j.csr.2014.01.003.

[62] S.E. Saye, D. van der Wal, K. Pye, S.J. Blott, Beach–dune morphological relationships and erosion/accretion: An investigation at five sites in England and Wales using LIDAR data, Geomorphology. 72 (2005) 128–155. doi:10.1016/j.geomorph.2005.05.007.

[63] R.G. Miller, Z.L. Hutchison, A.K. Macleod, M.T. Burrows, E.J. Cook, K.S. Last, Ben Wilson, Marine renewable energy development: assessing the Benthic Footprint at multiple scales, Front Ecol Environ. 11 (2013) 433–440. doi:10.2307/43187656?ref=no-x-route:47bb987c4f0cb8e9e50265ea6ba95d86.

[64] L. Airoldi, S.D. Connell, M.W. Beck, The Loss of Natural Habitats and the Addition of Artificial Substrata, in: Ecological Studies, Springer Berlin

Heidelberg, Berlin, Heidelberg, 2009: pp. 269–280. doi:10.1007/b76710_19.

[65] R. Inger, M.J. Attrill, S. Bearhop, A.C. Broderick, W.J. Grecian, D.J. Hodgson, C. Mills, E.V. Sheehan, S.C. Votier, M.J. Witt, B.J. Godley, Marine renewable energy: potential benefits to biodiversity? An urgent call for research, Journal of Applied Ecology. 46 (2009) 1145–1153.

[66] O. Langhamer, Artificial Reef Effect in relation to Offshore Renewable Energy Conversion: State of the Art, The Scientific World Journal. 2012 (2012) 1–8. doi:10.1023/A:1021352904712.

[67] E. Linley, T.A. Wilding, K. Black, A. Hawkins, Review of the reef effects of offshore wind farm structures and their potential for enhancement and mitigation, Report to the Department for Business, Enterprise and Regulatory Reform, London, 2007.

[68] D. Wilhelmsson, T. Malm, M.C. Öhman, The influence of offshore windpower on demersal fish, ICES Journal of Marine Science. 63 (2006) 775–784. doi:10.1016/j.icesjms.2006.02.001.

[69] M.J. Witt, E.V. Sheehan, S. Bearhop, A.C. Broderick, D.C. Conley, S.P. Cotterell, E. Crow, W.J. Grecian, C. Halsband, D.J. Hodgson, P. Hosegood, R. Inger, P.I. Miller, D.W. Sims, R.C. Thompson, K. Vanstaen, S.C. Votier, M.J. Attrill, B.J. Godley, Assessing wave energy effects on biodiversity: the Wave Hub experience, Philosophical Transactions of the Royal Society a: Mathematical, Physical and Engineering Sciences. 370 (2012) 502–529. doi:10.2307/41348248?ref=no-x-route:60912774e6a804d8451985c3f801a323.

[70] J. Sundberg, O. Langhamer, Environmental questions related to point-absorbing linear wave-generators: Impact, effects and fouling, in: Proceedings of the 6th European Wave and Tidal Energy Conference, Glasgow, Scotland, 2005.

[71] G. Keenan, C. Sparling, W. H, F. Fortune, SeaGen environmental monitoring programme final report, Marine Current Turbines, 2011.

[72] F. Bulleri, M.G. Chapman, The introduction of coastal infrastructure as a driver of change in marine environments, Journal of Applied Ecology. 47 (2010) 26–35. doi:10.1111/j.1365-2664.2009.01751.x.

[73] J. Birklund, S.B. Leonhard, Epibenthic communities, in: Offshore Windfarms and the Environment. the Danish Monitioring Programme: Final Results, Offshore Wind Farms and the Environment. The Danish Monitoring Programme: Final Results, 2006: p. 5.

[74] R.G. Miller, Z.L. Hutchison, A.K. Macleod, M.T. Burrows, E.J. Cook, K.S. Last, Ben Wilson, Marine renewable energy development: assessing the Benthic Footprint at multiple scales, Http://Dx.Doi.org/10.1890/120089. (2013).

[75] K. Griffith, S. Mowat, R.H. Holt, K. Ramsay, J.D. Bishop, G. Lambert, S.R. Jenkins, First records in Great Britain of the invasive colonial ascidian Didemnum vexillum Kott, 2002, Ai. 4 (2009) 581–590.

[76] K. Sambrook, R.H.F. Holt, R. Sharp, K. Griffith, R.C. Roche, R.G. Newstead, G. Wyn, S.R. Jenkins, Marine Policy, Marine Policy. 48 (2014) 51–58. doi:10.1016/j.marpol.2014.03.018.

[77] K. Bohn, C.A. Richardson, S.R. Jenkins, The distribution of the invasive non-native gastropod Crepidula fornicata in the Milford Haven Waterway, its northernmost population along the west coast of Britain, Helgol Mar Res. 69 (2015) 313–325. doi:10.1007/s10152-015-0439-2.

[78] P.I. Mitchell, S.F. Newton, N. Ratcliffe, T.E. Dunn, Seabird Populations of

Britain and Ireland, Poyser, London, UK, 2005.

[79] Ben Dean, R. Freeman, H. Kirk, K. Leonard, R.A. Phillips, C.M. Perrins, T. Guilford, Behavioural mapping of a pelagic seabird: combining multiple sensors and a hidden Markov model reveals the distribution of at-sea behaviour, Journal of the Royal Society Interface. (2012) rsif20120570. doi:10.1098/rsif.2012.0570.

[80] A. Shoji, K. Elliott, A. Fayet, D. Boyle, C. Perrins, T. Guilford, Foraging behaviour of sympatric razorbills and puffins, Marine Ecology. Progress Series. 520 (2015) 257–267. doi:10.3354/meps11080.

[81] S.C. Votier, S. Bearhop, M.J. Witt, R. Inger, D. Thompson, J. Newton, Individual responses of seabirds to commercial fisheries revealed using GPS tracking, stable isotopes and vessel monitoring systems, Journal of Applied Ecology. 47 (2010) 487–497. doi:10.1111/j.1365-2664.2010.01790.x.

[82] K. Kober, A. Webb, I. Win, M. Lewis, S. O'Brien, L.J. Wilson, J.B. Reid, An analysis of the numbers and distribution of seabirds within the British Fishery Limit aimed at identifying areas that qualify as possible marine SPAs, JNCC, 2010.

[83] C.B. Thaxter, B. Lascelles, K. Sugar, A.S.C.P. Cook, S. Roos, M. Bolton, R.H.W. Langston, N.H.K. Burton, Seabird foraging ranges as a preliminary tool for identifying candidate Marine Protected Areas, Biological Conservation. 156 (2012) 53–61. doi:10.1016/j.biocon.2011.12.009.

[84] B.E. Scott, R. Langton, E. Philpott, J.J. Waggitt, Seabirds and Marine Renewables: Are we Asking the Right Questions? in: Marine Renewable Energy, Springer Netherlands, Dordrecht, 2014: pp. 81–92. doi:10.1007/978-94-017-8002-5_7.

[85] R. Langton, I.M. Davies, B.E. Scott, Seabird conservation and tidal stream and wave power generation: Information needs for predicting and managing potential impacts, Marine Policy. 35 (2011) 623–630. doi:10.1016/j.marpol.2011.02.002.

[86] B. Wilson, R.S. Batty, F. Daunt, C. Carter, Collision risks between marine renewable energy devices and mammals, fish and diving birds, Scottish Executive, 2007.

[87] S. Benjamins, A.C. Dale, G. Hastie, J.J. Waggitt, M.-A. Lea, B.E. Scott, B. Wils, Confusion reigns? A review of marine megafauna interactions with tidal-stream environments, Oceanography and Marine Biology: an Annual Review. (2015) 1–54.

[88] J.J. Waggitt, P.W. Cazenave, R. Torres, Quantifying pursuit-diving seabirds' associations with fine-scale physical features in tidal stream environments, Journal of Applied …. (2016).

[89] J.J. Waggitt, B.E. Scott, Using a spatial overlap approach to estimate the risk of collisions between deep diving seabirds and tidal stream turbines: A review of potential methods and approaches, Marine Policy. 44 (2014) 90–97.

[90] K.J. Holm, A.E. Burger, Foraging Behavior and Resource Partitioning by Diving Birds During Winter in Areas of Strong Tidal Currents, Waterbirds. 3 (2002) 312–325.

[91] J.E. Zamon, Mixed species aggregations feeding upon herring and sandlance schools in a nearshore archipelago depend on flooding tidal currents, Marine Ecology. Progress Series. 261 (2003) 243–255.

[92] B. Williamson, P. Blondel, J. Waggitt, Using the FLOWBEC seabed frame to understand underwater interactions between diving seabirds, prey,

hydrodynamics and MREDs, Marine Renewable Energy Knowledge Ecxhange Programme. 03 (2015).

[93] O.O. Energy, Aquatera, M. Space, The Forward Look; an Ocean Energy Environmental Research Strategy for the UK, ORJIP, Stromness, 2015.

[94] B. Williamson, P. Blondel, Multibeam imaging of the environment around marine renewable energy devices, in: ECUA 2012 11th European Conference on Underwater Acoustics, Acoustical Society of America, 2012: p. 070051. doi:10.1121/1.4772810.

[95] J.K. Davies, A review of information relating to fish passage through turbines: implications to tidal power schemes, J Fish Biology. 33 (1988) 111–126. doi:10.1111/j.1095-8649.1988.tb05565.x.

[96] B. O'Driscoll, Ecological hazard identification of the Minesto “deep green commerical” tidal stream turbine, Goteborg, 2012.

[97] A. Marine, Collision risk of fish with wave and tidal devices, ABP Marine Environmental Research Ltd, Southhampton, 2010.

[98] S.H. Kramer, Evaluating the Potential for Marine and Hydrokinetic Devices to Act as Artificial Reefs or Fish Aggregating Devices, in: American Fisheries Society, Afs, Portland, Oregon, 2015.

[99] H.A. Viehman, G.B. Zydlewski, Fish Interactions with a Commercial-Scale Tidal Energy Device in the Natural Environment, Estuaries and Coasts. 38 (2014) 241–252. doi:10.1007/s12237-014-9767-8.

[100] M.J. Dadswell, R.A. Rulifson, Macrotidal Estuaries - a Region of Collision Between Migratory Marine Animals and Tidal Power Development, Biological Journal of the Linnean Society. 51 (1994) 93–113.

[101] The Crown Estate, Consolidation of wave and tidal EIA/HRA issues and research priorities, The Crown Estate, London, 2014.

[102] H.A. Viehman, G.B. Zydlewski, J.D. McCleave, G.J. Staines, Using Hydroacoustics to Understand Fish Presence and Vertical Distribution in a Tidally Dynamic Region Targeted for Energy Extraction, Estuaries and Coasts. 38 (2014) 215–226. doi:10.1007/s12237-014-9776-7.

[103] M.E. Baines, P. Evans, Atals of the Marine Mammals of Wales, CCW, 2012.

[104] G. Savidge, D. Ainsworth, S. Bearhop, N. Christen, B. Elsaesser, F. Fortune, R. Inger, R. Kennedy, A. McRobert, K.E. Plummer, D.W. Pritchard, C.E. Sparling, T.J.T. Whittaker, Strangford Lough and the SeaGen Tidal Turbine, in: A.I.L. Payne (Ed.), Marine Renewable Energy Technology and Environmental Interactions, Springer, 2014: pp. 153–172.

[105] B. McConnell, D. Gillespie, J. Gordon, G.D. Hastie, M. Johnson, J. Macaulay, Methods for tracking fine-scale underwater movements of marine mammals around marine tidal devices, Scottish Government, Edinburgh, 2013.

[106] B. Martin, C. Whitt, C. Mcpherson, A. Gerber, Measurement of long-term ambient noise and tidal turbine levels in the Bay of Fundy, in: Australian Acoustical Society, Freemantle, 2012.

[107] B. Wilson, S. Benjamins, J. Elliott, Using drifting passive echolocation loggers to study harbour porpoises in tidal-stream habitats, Endang. Species. Res. 22 (2013) 125–143. doi:10.3354/esr00538.

[108] J. Gordon, D. Thompson, R. Leaper, P. S, C. S V, J. Macaulay, T. Gordon, Studies of marine mammals in Welsh high tidal waters, Welsh Government, 2011.

[109] G.D. Hastie, D.M. Gillespie, J.C.D. Gordon, J.D.J. Macaulay, B.J. McConnell, C.E. Sparling, Tracking Technologies for Quantifying Marine

Mammal Interactions with Tidal Turbines: Pitfalls and Possibilities, in: Marine Renewable Energy, Springer Netherlands, Dordrecht, 2014: pp. 127–139. doi:10.1007/978-94-017-8002-5_10.

[110] C. Pierpoint, Harbour porpoise (Phocoena phocoena) foraging strategy at a high energy, near-shore site in south-west Wales, UK, J. Mar. Biol. Ass. 88 (2008) 1167–1173. doi:10.1017/S0025315408000507.

[111] D.P. Nowacek, L.H. Thorne, D.W. Johnston, P.L. Tyack, Responses of cetaceans to anthropogenic noise, Mammal Review. 37 (2007) 81–115. doi:10.1111/j.1365-2907.2007.00104.x.

[112] H. Slabbekoorn, N. Bouton, I. van Opzeeland, A. Coers, C. ten Cate, A.N. Popper, A noisy spring: the impact of globally rising underwater sound levels on fish, Trends Ecol Evol. 25 (2010) 419–427. doi:10.1016/j.tree.2010.04.005.

[113] J. Tougaard, Underwater Noise from a Wave Energy Converter Is Unlikely to Affect Marine Mammals, PLoS ONE. (2015).

[114] L.F. New, J. Harwood, L. Thomas, C. Donovan, J.S. Clark, G. Hastie, P.M. Thompson, B. Cheney, L. Scott Hayward, D. Lusseau, Modelling the biological significance of behavioural change in coastal bottlenose dolphins in response to disturbance, Functional Ecology. 27 (2013) 314–322. doi:10.1111/1365-2435.12052.

[115] E. Pirotta, R. Milor, N. Quick, D. Moretti, N. Di Marzio, Vessel noise affects beaked whale behavior: results of a dedicated acoustic response study, PLoS ONE. (2012).

[116] Ben Hickman, Magnetic Field Calculations for the Proposed Swansea Tidal Lagoon Cable Route, ERA Technology, 2014.

[117] CMACS, A baseline assessment of electromagnetic fields generated by offshore windarm cables., COWRIE, 2003.

[118] A.B. Gill, Offshore Renewable Energy: Ecological Implications of Generating Electricity in the Coastal Zone, Journal of Applied Ecology. 42 (2005) 605–615. doi:10.2307/3505894.

[119] A.B. Gill, M. Bartlett, F. Thomsen, Potential interactions between diadromous fishes of U.K. conservation importance and the electromagnetic fields and subsea noise from marine renewable energy developments, J Fish Biology. 81 (2012) 664–695. doi:10.1111/j.1095-8649.2012.03374.x.

[120] A. Moore, E.C.E. Potter, N.J. Milner, S. Bamber, The migratory behaviour of wild Atlantic salmon (Salmo salar) smolts in the estuary of the River Conwy, North Wales, Can. J. Fish. Aquat. Sci. 52 (1995) 1923–1935. doi:10.1139/f95-784.

[121] A. Moore, M. Ives, M. Scott, S. Bamber, The migratory behaviour of wild sea trout (Salmo trutta L.) smolts in the estuary of the River Conwy, North Wales, Aquaculture. 168 (1998) 57–68. doi:10.1016/S0044-8486(98)00340-8.

[122] A. Bark, B. Williams, B. Knights, Current status and temporal trends in stocks of European eel in England and Wales, ICES Journal of Marine Science: Journal Du Conseil. 64 (2007) 1368–1378.

[123] M.C. Öhman, P. Sigray, H. Westerberg, Offshore windmills and the effects of electromagnetic fields on fish, AMBIO: a Journal of the Human Environment. 36 (2007) 630–633.

[124] A.B. Gill, J.A. Kimber, The potential for cooperative management of elasmobranchs and offshore renewable energy development in UK waters, J. Mar. Biol. Ass. 85 (2005) 1075–1081. doi:10.1017/S0025315405012117.

[125] M.A. Shields, D.K. Woolf, E.P.M. Grist, S.A. Kerr, A.C. Jackson, R.E.

Harris, M.C. Bell, R. Beharie, A. Want, E. Osalusi, S.W. Gibb, J. Side, Ocean & Coastal Management, Ocean and Coastal Management. 54 (2011) 2–9. doi:10.1016/j.ocecoaman.2010.10.036.

[126] M. Kadiri, R. Ahmadian, B. Bockelmann-Evans, R.A. Falconer, D. Kay, An assessment of the impacts of a tidal renewable energy scheme on the eutrophication potential of the Severn Estuary, UK, Comput Geosci. 71 (2014) 3–10. doi:10.1016/j.cageo.2014.07.018.

[127] R.J.K. Wood, A.S. Bahaj, S.R. Turnock, L. Wang, M. Evans, Tribological design constraints of marine renewable energy systems, Philosophical Transactions: Mathematical, Physical and Engineering Sciences. 368 (2010) 4807–4827. doi:10.2307/25753441?ref=no-x-route:47bb987c4f0cb8e9e50265ea6ba95d86.

[128] G.W. Boehlert, G.R. McMurray, C.E. Tortorici, Ecological effects of wave energy development in the Pacific Northwest, Memorandum NMFS-F/SPO (2008).

[129] B. Polagye, A. Copping, K. Kirkendall, Environmental effects of tidal energy development: a scientific workshop, in: Seattle, 2010.

[130] M.J. Kennish, Practical Handbook of Marine and Estuarine Pollution, CRC Press, New York, 1997.

[131] T.J. Smayda, Complexity in the eutrophication–harmful algal bloom relationship, with comment on the importance of grazing, Harmful Algae. 8 (2008) 140–151. doi:10.1016/j.hal.2008.08.018.

[132] T.J. Smayda, Bloom dynamics: physiology, behavior, trophic effects, Limnology and Oceanography. 45 (1997) 1132–1136.

[133] E. Berdalet, L.E. Fleming, R. Gowen, K. Davidson, P. Hess, L.C. Backer, S.K. Moore, P. Hoagland, H. Enevoldsen, Marine harmful algal blooms, human health and wellbeing: challenges and opportunities in the 21st century, J. Mar. Biol. Ass. 96 (2015) 61–91. doi:10.1017/S0025315415001733.

[134] J.H. Landsberg, The Effects of Harmful Algal Blooms on Aquatic Organisms, Reviews in Fisheries Science. 10 (2002) 113–390. doi:10.1080/20026491051695.

[135] G.M. Hallegraeff, A review of harmful algal blooms and their apparent global increase, Phycologia. 32 (1993) 79–99. doi:10.2216/i0031-8884-32-2-79.1.

[136] P. Grandjean, D. Ozonoff, Centers for Oceans and Human Health: a unified approach to the challenge of harmful algal blooms, Environmental Health. 7 (2008).

[137] S.K. Moore, V.L. Trainer, N.J. Mantua, M.S. Parker, E.A. Laws, L.C. Backer, L.E. Fleming, Impacts of climate variability and future climate change on harmful algal blooms and human health, Environmental Health. 7 (2008). doi:10.1186/1476-069X-7-S2-S4.

[138] P. Devine-Wright, Public engagement with renewable energy: Introduction, in: Renewable Energy and the Public: From NIMBY to Participation, Earthscan, London, 2011.

[139] A. Kollmuss, J. Agyeman, Mind the Gap: Why do people act environmentally and what are the barriers to pro-environmental behavior? Env. Educ. Res. 8 (2002) 239–260. doi:10.1080/13504620220145401.

[140] I.J. Onakpoya, J. O'Sullivan, M.J. Thompson, C.J. Heneghan, The effect of wind turbine noise on sleep and quality of life: A systematic review and meta-analysis of observational studies, Environment International. 82 (2015) 1–9. doi:10.1016/j.envint.2015.04.014.

[141] Scottish Natural Heritage, Siting and Designing windfarms in the landscape, Edinburgh, 2009.
[142] A. Honda, J. Wiwattanapantuwong, T. Abe, Journal of Environmental Psychology, Journal of Environmental Psychology. 40 (2014) 147–156. doi:10.1016/j.jenvp.2014.06.003.
[143] T. Fanning, C. Jones, M. Munday, The regional employment returns from wave and tidal energy: A Welsh analysis, Energy. 76 (2014) 958–966. doi:10.1016/j.energy.2014.09.012.
[144] The National Trust, Valuing our Environment, The National Trust, 2006.
[145] Nautilus Constultants, Study into Inland and Sea Fisheries in Wales, National Assembly for Wales, 2000.
[146] Welsh National Marine Plan, Welsh Government, n.d. http://www.gov.wales (accessed January 11, 2016).
[147] S. Kaplan, The restorative benefits of nature: Toward an integrative framework, Journal of Environmental Psychology. 15 (1995) 169–182.
[148] K. Walker-Springett, Options for marine renewable energy developements off the Llyn Penninsula: assessment of options and public opinion, CAMS Report, Bangor, 2015.
[149] K.A. Alexander, T. Potts, T.A. Wilding, Marine renewable energy and Scottish west coast fishers: Exploring impacts, opportunities and potential mitigation, Ocean and Coastal Management. 75 (2013) 1–10. doi:10.1016/j.ocecoaman.2013.01.005.
[150] P. Devine Wright, Beyond NIMBYism: towards an integrated framework for understanding public perceptions of wind energy, Wind Energ. 8 (2005) 125–139. doi:10.1002/we.124.
[151] P. Devine-Wright, Reconsidering public attitudes and public acceptance of renewable energy technologies: a critical review, Manchester, 2007.
[152] R. Wüstenhagen, Social Acceptance of Wind Energy Projects, IEA Wind, 2008.
[153] P. Upham, S. Shackley, The case of a proposed 21.5 MWe biomass gasifier in Winkleigh, Devon: Implications for governance of renewable energy planning, Energy Policy. 34 (2006) 2161–2172. doi:10.1016/j.enpol.2005.04.001.
[154] J. Zoellner, P. Schweizer-Ries, C. Wemheuer, Public acceptance of renewable energies: Results from case studies in Germany, Energy Policy. 36 (2008) 4136–4141. doi:10.1016/j.enpol.2008.06.026.
[155] C. Gross, Community perspectives of wind energy in Australia: The application of a justice and community fairness framework to increase social acceptance, Energy Policy. 35 (2007) 2727–2736. doi:10.1016/j.enpol.2006.12.013.

Table

Research Challenge	Importance/Priority level	Existing level of knowledge	Present research level
Cumulative regional scale impacts of multiple marine renewable energy device arrays	Medium	Low	Low
Effects of scaling up from individual test devices to commercial arrays	High	Low	Low
Fine-scale functional use, foraging and diving behaviour at MREI sites by top predators	High	Low	Medium
Interactions between MREIs and coastal/offshore sediment transport, deposition and erosion patterns	Medium	Medium	Medium
Active monitoring during device operation and assessment of marine mammal behavioural response	High	Low	Medium
Socio-economic impacts and public perceptions of MREIs	High	Low	Low
Biological and chemical contaminant impacts and associated transport pathways	Medium	Low	Low
Localised habitat alterations and ecosystem impacts of novel habitat provision	Medium	Medium	High
Implications for marine invasive species survival, reproduction and range expansion	Medium	Low	High
Alterations of turbidity, light attenuation, and primary productivity affecting biogeochemical cycling	Low	Low	Low

Figure 1

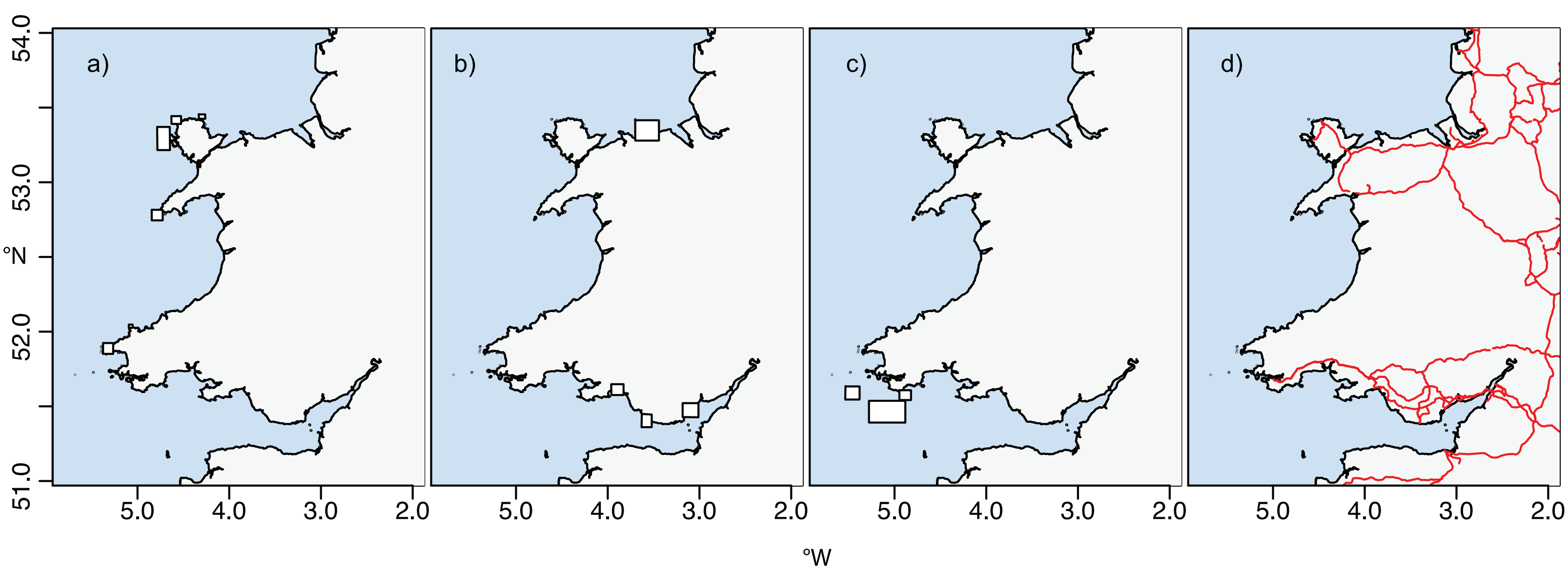

Figure 2

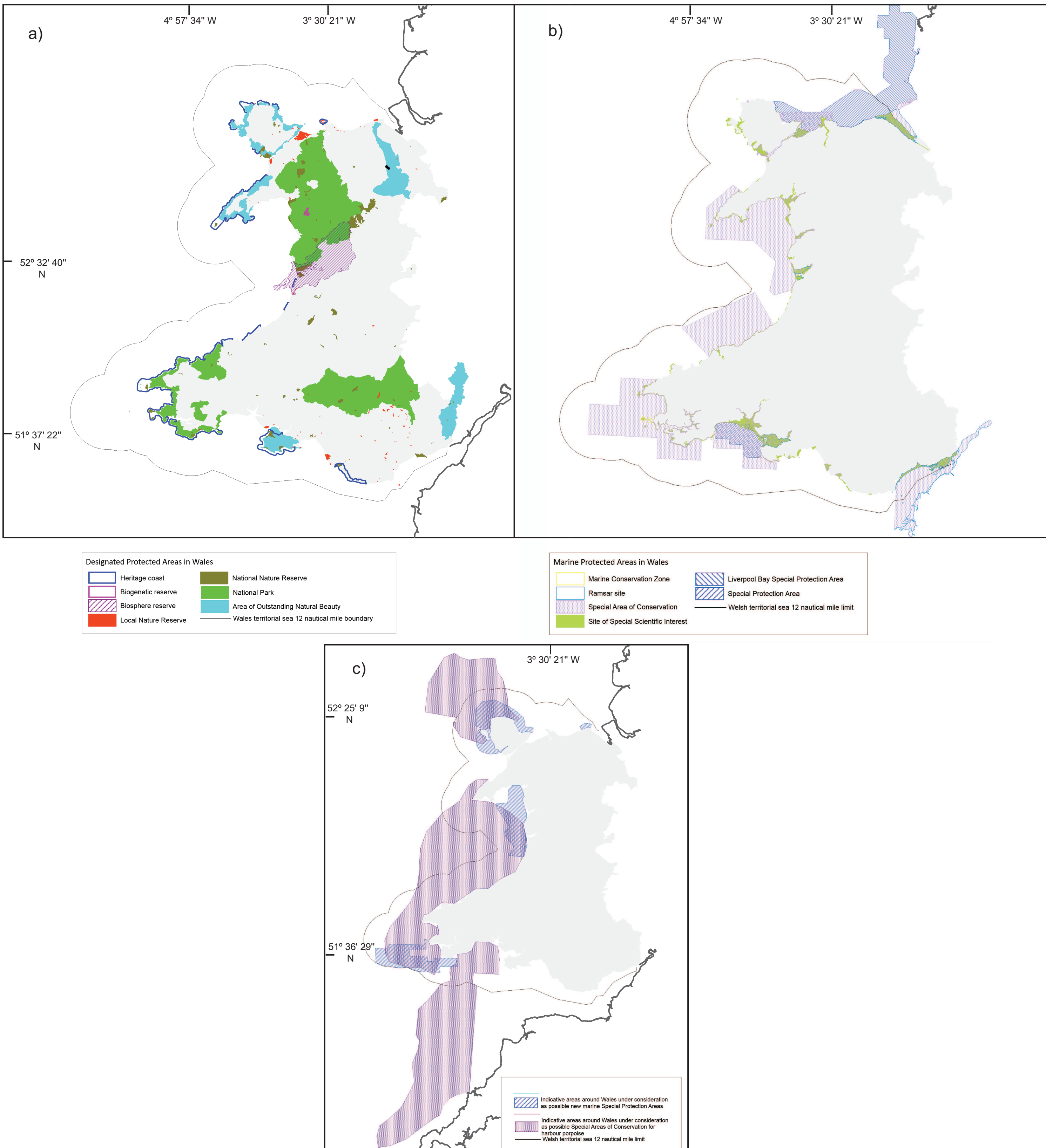
a)
4° 57' 34" W
3° 30' 21" W
52° 32' 40" N
51° 37' 22" N
b)
4° 57' 34" W
3° 30' 21" W
Designated Protected Areas in Wales
Heritage coast
Biogenetic reserve
Biosphere reserve
Local Nature Reserve
National Nature Reserve
National Park
Area of Outstanding Natural Beauty
Wales territorial sea 12 nautical mile boundary
Marine Protected Areas in Wales
Marine Conservation Zone
Ramsar site
Special Area of Conservation
Site of Special Scientific Interest
Liverpool Bay Special Protection Area
Special Protection Area
Welsh territorial sea 12 nautical mile limit
c)
3° 30' 21" W
52° 25' 9" N
51° 36' 29" N
Indicative areas around Wales under consideration as possible new marine Special Protection Areas
Indicative areas around Wales under consideration as possible Special Areas of Conservation for harbour porpoise
Welsh territorial sea 12 nautical mile limit

Figure 3

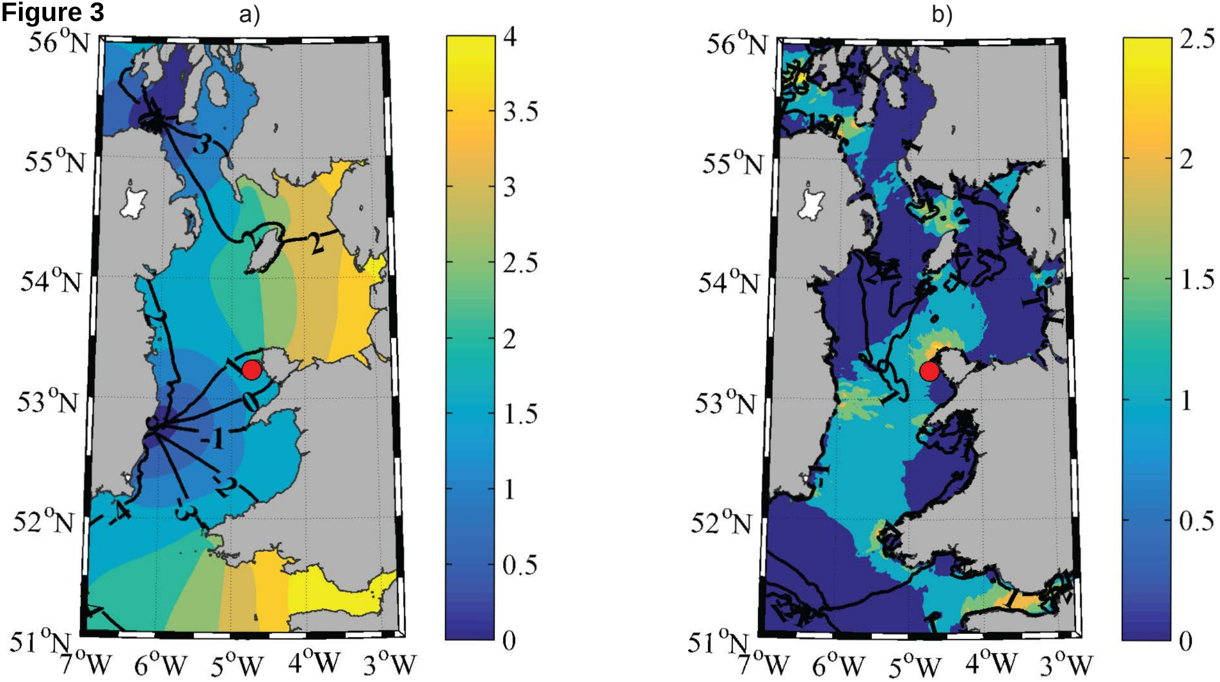

Figure 4
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